Incorporating Data Link Features into a Multi-Function Display to Support Self-Separation and Spacing Tasks for General Aviation Pilots

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ABSTRACT
One objective of the Small Aircraft Transportation System (SATS) Higher Volume Operations (HVO) project is to increase the capacity and utilization of small non-towered, non-radar equipped airports by transferring traffic management activities to an automated Airport Management Module (AMM) and separation responsibilities to general aviation (GA) pilots. Implementation of this concept required the development of a research Multi-Function Display (MFD) to support the interactive communications between pilots and the AMM. The interface also had to accommodate traffic awareness, self-separation, and spacing tasks through dynamic messaging and symbology for flight path conformance and conflict detection and alerting (CDA). The display served as the mechanism to support the examination of the viability of executing instrument operations designed for SATS designated airports. Results of simulation and flight experiments conducted at the National Aeronautics and Space Administration's (NASA) Langley Research Center indicate that the concept, as facilitated by the research MFD, did not increase pilots' subjective workload levels or reduce their situation awareness (SA). Post-test usability assessments revealed that pilots preferred using the enhanced MFD to execute flight procedures, reporting improved SA over conventional instrument flight rules (IFR) procedures.

KEYWORDS
Small Aircraft Transportation System, SATS Higher Volume Operations, MFD and SATS, Data Link Messaging

INTRODUCTION
The Small Aircraft Transportation System (SATS) research project, a partnership between NASA, the National Consortium of Aviation Mobility, and the Federal Aviation Administration (FAA), is investigating many new challenges for instrument flight and technology development for general aviation (GA) aircraft that range from small single engine fixed wing aircraft to business jets and helicopters.

A critical aspect of NASA's challenge is associated with designing an experimental Multi-Function Display (MFD) to aid pilots in performing instrument flight rules (IFR) procedures at non-towered, non-radar (NTNR) airports as part of a SATS Higher Volume Operations (HVO) concept. Although an optimized interface was not the primary purpose of the research endeavor, inherent in the design of the display was its ability to transform communications data into accurate visual information about the state of inbound and outbound airport operations through dynamic messaging and traffic symbology. The MFD interface served as the conduit for the communication of sequence, position, and conflict detection and alerting (CDA) cues critical to the SATS-HVO concept. This paper describes the design of a display as a decision support tool to enable pilots to self-separate and space from aircraft operating at SATS designated airports.

Background
Currently, during instrument meteorological conditions (IMC) at NTNR airports, air traffic control (ATC) uses procedural separation limiting IFR operations to one approaching or departing aircraft at a time – a capacity-limiting paradigm. The SATS HVO concept breaks this paradigm and increases operational efficiency by allowing multiple, simultaneous operations [1].

Central to the SATS HVO concept is a set of procedural rules that enable self-separation and enhance throughput in a newly defined area of flight operations - a Self-Controlled Area (SCA) activated during periods of IMC. It is envisioned that pilots will use advanced airborne systems to execute procedures in the SCA by relying on automated dependent surveillance-broadcasts (ADS-B), two way data link, and appropriate self-separation tools. Sequencing is enabled by an airport management module (AMM), a ground-based automated system typically located at the airport, that will provide sequencing information to arriving aircraft. In contrast to ATC, the AMM will not provide separation, clearances, or altitude assignments and will not control aircraft or sequence departures.

Additionally, the SATS HVO concept employs a procedure (Figure 1) adapted from the the Terminal Arrival Area basic "T" approach [2] to aid in the sequencing of traffic. Pilots will either make a vertical or lateral entry into the SCA. For a vertical entry, the aircraft (red aircraft at 4000 ft) descends at increments of 1000 ft from a transition fix, outside the SCA, following other traffic within the airspace. If there are no other aircraft at the initial approach fix (IAF) to which the aircraft is assigned, a lateral entry directly to the IAF is possible (blue aircraft at 2000 ft).

The "T" approach geometry, the HVO procedure that ensures the smooth flow of traffic along with the communications requirements and software tools for spacing, separation and CDA are the basis of the MFD design.

DEVELOPMENT OF THE SATS HVO RESEARCH MULTI-FUNCTION DISPLAY (MFD)

The platform for the research interface, a modification of an Avidyne® EX5000 MFD, was selected because one was installed in NASA Langley Research Center's (LaRC) Cirrus SR22 (Figure 2). The interface was reproduced for a human-in-the-loop simulation experiment with the functionality being carried over to a flight experiment. The researchers examined the Avidyne® display's existing capabilities to facilitate the integration of SATS requirements necessary to achieve the HVO concept's objectives (i.e., the ability to self-separate, avoid conflicts, communicate with the AMM, and display traffic information).

The challenge for the research psychologists was to prescribe, design, and position messaging elements required to convey critical data relevant to the pilot's role in self-separation, self-spacing, and executing the IFR procedure. Consideration for the pilot's instrument scan and mental workload was important since the display was intended to augment the information provided by the primary flight displays without depleting attentional resources [3]. Additionally, display requirements, where possible, needed to provide messaging, features, and symbols that were compliant with industry standards. Assumptions guiding the display design included: 1) retaining useful features of the Avidyne® display; 2) redefining some of the softkey actions to facilitate interaction with the AMM and the aircraft control and navigation systems; 3) gating data link messages to dedicated windows on the MFD; 4) easing search tasks via the location of text windows and map symbology; 5) making color, size, and shape coding distinctive, intuitive, and salient; and 6) using phraseology as close to the current ATC lexicon as possible. The final and critical assumption for text commands was that the messaging should be advisory only and not construed as a controller for flight operations.

Task Analysis and Requirements Identification

Based on the approach described above, a "typical IFR" flight was disaggregated into higher order tasks incuding: communications requirements (with ATC and/or AMM) for entry or approach to the airport (depending on whether a flight was a current day "baseline" flight or a SATS flight); initiating a procedure segment such as entering the airport or SATS airspace, descending to a lower altitude or directly to the IAF, holding at waypoints or fixes descents or climbs, or holding at the IAF, initiating the approach, executing a missed approach, or landing or departing.

For each task, information requirements, actions to make electronic requests or retrieve information, and modalities for representing information were identified. Coupled tone-text presentations or aural alerts were not implemented due to time and funding limitations.

The underlying rule – that the AMM was not a controller – drove the phraseology for the messaging system so that the pilot took responsibility for processing information and making decisions based on the data received. Rather than display a message such as "… cleared to 2000," the message "OPEN: 2000" was used to indicate that the pilot could descend or advance along the approach path if no aircraft was located ahead of the ownship at the stated altitude (a safe vertical and horizontal distance was assured thereby preventing a conflict with another aircraft).

Map elements and related symbology

The features of the Avidyne® MFD that were retained and layered on top of the moving map included: the active way point window, flight path renderings and color coding, a top mounted and centered digital course indicator, a heading scale with range indication, and range knobs (right and left respectively). Menu tabs at the lower right were disabled.

Crucial to the task of self-separation was the pilot's requirement to understand the status of the airspace and the airport within the SCA. Standards for electronic displays vary among organizations allowing some flexibility in coding, selecting designs, and locating windows for gating data linked information. Traffic information and symbology were incorporated into the display so that the pilot could identify the lead aircraft and differentiate the lead from other traffic. Rather than use range buffers to indicate protected zones that might intersect, pilots were cued by an alert message and "Pilot Advisor" (PA) message indicating that their airspeed or flight path deviations might be impacting operations. The range scale helped pilots orient the ownship relative to other traffic or the airport depending on the segment of flight. Data tags with registration numbers, ground speed, climb and descent arrows [based on traffic alert and collision avoidance (TCAS) II guidelines], and relative altitudes were added to facilitate situation awareness (SA), reduce scan to acquire targets and maintain self-separation and spacing [4]. Dashed lines were used to indicate missed approach paths in concert with IFR charting symbology.

Adhering to the SATS HVO procedure should prevent the intrusion of one aircraft upon another. However, an important requirement included indicating when the proximity of an aircraft might pose a conflict. Look-ahead times were based on time and distance considering the aircraft speed profiles and state vectors. TCAS II color-coding was used in algorithms for conflict detection but stopped short of providing resolutions. The traffic aircraft symbols were chevrons (providing intuitive directional information) that changed color and characteristic to provide redundant coding, rather than shape changes prescribed by the TCAS [4, 5].

Dynamic Messaging

Information changes rapidly in the SATS environment with continuous air-air and ground-air broadcasts providing cues to the pilot toward executing the procedure along with traffic position, data tags, and CDA alerts if required. ADS-B data linked information is transformed into messages and dynamic elements used by the piot to make decisions regarding when to follow the preceding aircraft and maintain self-separation. If transgressions from the flight path and performance profile occur, the aircraft system advises the pilot that speed, heading, or altitude should be adjusted to prevent loss of separation from traffic aircraft.

Except during departures, no communications between controller and pilot are required once the aircraft enters the SCA. Inside the SCA, the pilot uses the Common Traffic Advisory Frequency (CTAF) to announce intentions for party line communications with other aircraft. This data is supported by traffic symbology

Text Windows and Gated Data Link Messages

Based on Drury's model of intelligent search, messaging windows were sited to guide the pilot's attention to specific elements [3]. For example, data transmitted by the AMM (i.e., airport identifier, approach, missed approach fixes, and sequence data) are depicted in a dedicated AMM window. Similarly, flight path conformance, speed, and altitude transgressions, based on a speed profile and a defined containment area, appear in a dedicated PA window.

The researchers positioned three windows in the upper periphery of the display, level with the pilot's lateral scan. The alert window was placed in the upper left corner, and the AMM and PA windows were situated in the upper right corner below the active waypoint window (Figure 2). The following are highlights of each window's features.

Alert Window: The alert window (Figure 3) merges data link information from both the AMM and the ADS-B broadcasts, advising the pilot of the location of new or changed information. Aged alerts deselect themselves, and the window disappears. Alerts include: "AMM" to indicate messaging in the AMM window; "REQ SEQ" to the pilot may request a sequence; "Advisor" to direct attention to the PA window for procedural information; “Message” to advise the pilot of new messages accidble using the “MSG>” button (right side of the display in Figure 2); and “Traffic” (in reverse background amber or red) to alert the pilot to impending conflicts.

AMM Window: The AMM window (Figures 2 and 4) provides airport information similar to a flight plan. When a sequence request is made, the AMM determines the aircraft’s position in relation to other aircraft within the vicinity and in the SCA providing a sequence to that aircraft. Figure 4 illustrates a vertical entry notification, the airport identifier, and IAF . The sequence is in the form of “FOLLOW: <aircraft identification>” rather than a queue number. The fourth line shows the approach filed (GPS approach 03) and the missed approach holding fix . Mature information disappears as the pilot proceeds along the approach. For example, upon entering the SCA, entry and airport information clears. As the aircraft becomes the first for landing, “FOLLOW: N022GC” updates to “FOLLOW: NONE.” Only the approach type and missed approach remain.

PA Window: Procedure information is gated to the PA window below the AMM window. The PA (Figure 5) provides information indicating when the aircraft is out of conformance with the flight path, when airspace below is available for maneuvering, the total time before an approach can be initiated, and when the approach is open for initiation. For example, Figure 5 illustrates the progression of messages for pilots on a vertical approach. “OPEN:3000” indicates that the pilot may descend to 3000 ft, and “Open:2000” indicates that the pilot may descend to the IAF at 2000 ft. If a hold is required when the pilot arrives at the IAF, a time to approach (TTA) is highlighted, providing a count down to “OPEN:Approach” to initiate the approach. This information is based on a self-spacing algorithm considering lead aircraft position and airspeed and can change if that aircraft adjusts airspeed or flight path. Messages associated with urgent flight path conformance transgressions are blue advising the pilot that adjustments in altitude, airspeed, or course are warranted.

Softkeys

The Avidyne® MFD has five softkeys located on each side of the screen on the display bezel (Figures 2 and 6). Several of the softkeys were redefined as on-condition buttons to accommodate the requirements of operating in a SATS environment and were dedicated to sequence requests and next leg functions. The on-condition labels, adjacent to the buttons, appear during appropriate segments of flight and contain sublabels that support a segment-specific task. For example, the “SEQUENCE” label with a corresponding sublabel - “Request” - commands an action to request entry into the SCA. Upon pressing the softkey, the sublabel changes to “Cancel” indicating that, if desired, the pilot may cancel a request for sequencing. The “Next Leg” button is pressed to provide flight path guidance to skip or exit a hold or to execute a missed approach. “Skip Hold” indicates the pilot does not need to hold at the IAF, and pressing this button renders the flight path from that waypoint. “Exit Hold” appears when the pilot enters a hold and is pressed when the pilot is capable of initiating the approach. The button labels appear *only* when an action is required and disappear after buttons are pressed.

Right side softkeys control display features such as ownship position, decluttering, and message retrieval. Ownship position orientation and decluttering were pilot selectable features. The message feature (“MSG>” in Figure 2) was the access button for retrieving automatic terminal information services (ATIS) information in the form of a popup window in the lower center portion of the screen above the disabled menutabs. That window was visible at the pilot’s discretion with the sublabel indicating “show” or “hide” rather than timing out. The ATIS provided weather and airport information along with the number of operations and requests for sequencing in the SCA. Scroll capability for lengthy messages was available via up and down arrows. This feature was not implemented for the flight experiment.

Informal Usability Evaluation

Once the display’s general design was formulated, a SATS-HVO procedure storyboard was created to conduct an informal evaluation of the design to identify issues that pilots might have with interpreting display elements prior to a final implementation . Three in-house, instrument rated pilots examined the display features as they were walked through the procedure. Based on the task analysis, each flight segment was presented in a separate, static image of the interface with attendant cues from all prescribed messaging windows and softkeys. The evaluation pilots (EPs) were asked to examine text messages, labels, symbology, popup windows, dwell times, and element positions.

Messaging windows: EPs suggested the alert window demanded too much attention and that presenting alerts for more than one message element might be confusing. This concern was alleviated when advised that simultaneous alerts would be presented hierarchically.

Alerts: The desire for coupled tone-text alerts was noted as a means to alleviate scan requirements. However, aural alerts could not be implemented during this phase of experimentation.

ATIS popup window: The ATIS window provided plain text weather data followed by the number of SCA sequence requests and operations. EPs liked the window but wanted a selectable plain text or METARs capability. One noted benefit included offloading writing tasks associated with transcribing aural ATIS communications. The window's position (across the bottom of the screen) generated discussion as to whether or not it was obscuring important map data. The requests and operations data was largely considered to be irrelevant.

Phraseology: Care was taken in selecting words that would not imply the AMM was providing a clearance or that the PA was commanding pilots' actions. Initially, EPs preferred using current ATC phraseology (i.e., "cleared for…" instead of "OPEN:<altitude>" or "expect further clearance" rather than "standby"). As the evaluation proceeded, EPs became accustomed to the "OPEN" message interpretation. The notion of "Entry:lateral or vertical" in the AMM window was confusing to the EPs. Their rationale was that based on the PA altitude message and the FAA release into the SCA, the entry type should be intuitive.

Feedback: On-conditions buttons provide feedback through their disappearance or change in sublabel – the only confirmation of pilot's inputs. Some EPs wanted additional verification that their sequence request had been received. Secondary feedback for this action is, however, provided by the appearance of "standby" or absolute AMM instructions in the AMM window without saying specifically – "request received."

Data tags: Initially, the data tags that float with the traffic symbols included the aircraft identification (ID), the relative distance, climb or descent arrows, and relative altitude. The relative distance was deemed unnecessary by EPs and, at their recommendation, was replaced by airspeed.

Overview of the survey: Generally, EPs felt some of the display features would be better understood had they been able to interact with a simulated flight scenario. Although the advisory terminology was retained for the simulation and flight experiments, several recommendations were implemented such as replacing the relative distance with airspeed and retaining the active waypoint window. A recommendation for the missed approach path to be displayed as a dashed line in concert with charting symbology was also accepted. Several recommendations could not be implemented due to time and funding constraints. However, these recommendations will be considered during future redesign efforts. Overall, the informal evaluation gave us confidence in the basic design to accomplish the procedures defined in the concept of operations.

ROLE OF THE MFD DURING SIMULATION AND FLIGHT EXPERIMENTS

The general purpose of the simulation and flight experiments was to answer the questions: "Can pilots safely and proficiently fly an airplane while performing SATS HVO procedures?" and "Do pilots perceive that workload, while performing HVO procedures, is no greater than flying in today's system?" Dependent subjective measures included workload and SA including traffic and navigation guidance awareness. While the experiments were not formal evaluations of the interface design, the displays were the enabling conduit of the information and hence, data obtained is reflective of it's effectiveness.

Fifteen EPs in the simulation experiment and 12 EPs (drawn from the simulation experiment's participant pool) in the flight experiment were asked to fly both baseline (i.e., current day) scenarios and corresponding SATS HVO scenarios (using the experimental MFD). The simulation and flight experiments were conducted in the spring and summer of 2004. During the simulation experiment, each EP used a GA desktop simulator to fly five baseline flight scenarios (using the moving map with traffic symbols but no messaging windows) and five corresponding HVO procedures (using the enhanced display). EPs also received tailored approach plates for the experiments' airport. Four of the procedures were flown independently by each EP using scripted traffic and included: 1) a departure, 2) a lateral entry approach, 3) a vertical entry approach, and 4) a missed approach. The fifth scenario was a “multi-pilot scenario” in which four GA desktop simulators were linked and EPs were instructed to complete vertical approaches. Neither multi-pilot nor departure scenarios were flown during the flight experiment.

Post-Scenario Subjective Assessments: Two subjective assessments were administered after each scenario during the simulation and flight experiments. The Modified Cooper Harper (MCH) Rating Scale [6] was used to obtain workload ratings that could range from “1” (low) to “10” (high). The Situational Awareness Rating Technique (SART) [7] (comprised of three SA dimensions (understanding, demand, and supply) and two independent dimensions of traffic and navigation guidance awareness) was used. An overall SA rating associated with understanding, demand, and supply could range from “1” (low) to “14” (high), and SA ratings associated with traffic awareness and navigation guidance awareness could range from “1” (low) to “7” (high).

Usability: A post-simulation, 17-item questionnaire was administered to EPs querying their attitudes toward the HVO procedures, messaging, phraseology, symbology, and overall design of the display. Questions were rated on a value scale of four to seven qualities depending on the item being assessed. Positive values (i.e. “very easy” or “very useful”) were rated on the low side of the scale while negative attributes (i.e. “extremely difficult” or “not useful at all”) were rated on the high end of the scale. Narrative comments were solicited as well.

Summary results associated with subjective assessments of workload and SA (including traffic and navigation guidance awareness) are provided in general terms only. Detailed results of the statistical analyses will be provided in future publications. Usability results and comments follow the discussion of the MCH and SART evaluations.

Simulation Experiment Results

EPs used the MCH Rating Scale [6] to rate the workload level experienced during each of the simulation experiment’s 10 test conditions. Workload ratings averaged across the five types of flight scenarios indicated that EPs experienced a lower workload level when performing the SATS procedures [Mean (M) = 1.69, Standard Deviation (SD) = 0.54] and than when performing the baseline procedures (M = 2.59, SD = 1.37) (Figure 7).

For the dimensions of SA queried by the SART (i.e. understanding, demand and supply), traffic awareness, and navigation guidance awareness, Figure 7 illustrates that EPs achieved a higher level of SA [where SA = understanding – (demand – supply)] during the SATS procedures (M = 9.6, SD = 1.97) than the baseline procedures (M = 8.05, SD = 2.68); EPs achieved greater traffic awareness during the SATS procedures (M= 6.55, SD = 0.72) than the baseline procedures (M = 5.59, SD = 1.43); and EPs achieved nav-guidance awareness during the SATS procedures (M = 6.45, SD = 0.65) than the baseline procedures (M = 5.44, SD = 1.30). This suggests that the display, as the medium for conveying the SATS HVO concept, was effective in communicating the visual and textual information necessary to perform the procedure without increasing workload or reducing SA, traffic awareness, or navigation guidance awareness.

Flight Experiment Results

EPs used the MCH Rating Scale [6] to rate the workload level experienced during each of the flight experiment’s eight test conditions. Workload ratings, averaged across the five types of flight scenarios, indicated that EPs experienced a lower workload level when performing the SATS procedures (M = 1.57, SD = 0.43) than when performing the baseline procedures (M = 2.35, SD = 0.62) (Figure 8).

For the dimensions of SA, Figure 8 illustrates that EPs achieved higher levels of SA, traffic awareness, and navigation guidance awareness when performing SATS procedures (SA: M = 7.74, SD = 1.84; Traffic Awareness: M = 6.33, SD = 0.77; and nav-guidance Awareness: M = 6.43, SD = 0.48) than when performing baseline procedures (SA: M = 6.03, SD = 2.46; Traffic Awareness: M = 5.44, SD = 1.47; and Navigation Guidance Awareness: M = 5.29, SD = 1.40). Since the display delivers the visual elements critical to SA, it is suggested that the display’s features played an instrumental role in EPs’ abilities to fly the SATS HVO procedure without increasing workload or reducing SA, traffic or navigation guidance awareness.

While a formal simulation to flight experiment data comparison has not yet been completed, similar results of lower workload, higher SA, traffic and navigation guidance awareness for the SATS HVO scenarios over the baseline scenarios were found in both studies.

USABILITY EVALUATION

The usability questionnaire was comprised of two parts: SATS-HVO procedure questions and MFD questions. It was important to investigate the EPs' attitudes toward the ease of use or complexity of the procedures as their perceptions can be used to optimize the procedures. Generally, EPs liked the new procedures: 100% of the respondents indicated the procedures were "easy to follow" to "very easy to follow." The procedures were significantly less complicated than current day IFR to 33% of the EPs. None of the EPs felt the SATS procedures were more difficult than the baseline procedures.

The MFD questions were designed to obtain EPs' perceptions of the display elements' ability to aid decision-making. For the purposes of centering the discussion on the MFD as the medium for conveying the concept and the procedure, only the MFD issues will be highlighted.

MFD Features

The purpose of the usability questionnaire was to investigate how EPs used the MFD's windows; to assess the clarity of the messaging strategy; to determine if the PA provided adequate cueing to the EPs; to analyze how useful the sequencing information was; and to explore how display features such as messaging, cueing, symbols, and characteristics could be enhanced to improve the display's effectiveness. The following discussion provides highlights of responses to the questionnaire.

- Alert window: EPs were mixed in their responses. Although 47% of the EPs thought the Alert Window was "very useful," 27% rated it as "useful," and 13% were "undecided." Another 13% felt the Alert window was "not useful at all." Several EPs recommended either aural tones or blinking to aid in the capture of alert presentation.
- AMM window: 60% of the EPs thought the AMM window was "very useful," while 33% rated it as "useful," and 7% were "undecided." None of the EPs felt the AMM window was "not useful." Written comments indicated the AMM window provides good, continuous reference information, eliminating scribing tasks. Several respondents felt "Entry;<type>" was unnecessary.
- Pilot Advisor: 93% of the respondents indicated the PA was at least "useful," with 53% of those reporting "very useful." Respondents cited that the PA's ability to inform pilots of flight path transgressions when maneuvering aided in next-step planning. The urgent PA messages were helpful, but some were considered annoying (e.g., "monitor speed" and "monitor altitude").
- Moving Map: 93% of the respondents described the moving map as "very useful" while 7% described it as "useful." The primary benefit expressed was SA and traffic awareness.
- Text information: text color used as a means for cueing and differentiating between the AMM and the PA was considered at least "useful" by 67% of the EPs; 20% were "undecided," and 13% felt it "wasn't useful at all." Several comments focused on the ability of color to help the pilot process different types of information. Font sizes were reported appropriate with 93% reporting at least "somewhat appropriate" or better. Good legibility was a common response.
- Symbol characteristics: 73% of the EPs indicated the symbolic information was at least "appropriate," 20% **-** "somewhat appropriate" with only 7% "undecided." None of the EPs rated the symbols as being "inappropriate" or worse. Generally, EPs felt the symbols aided quick recognition of the elements after just a few approaches.

CONCLUSIONS

The experimental MFD used in the validation of the SATS HVO concept served as the interface between the components of the system and the pilot to provide traffic, AMM, and procedural information. Pilots flying the procedures indicated that the ability of dynamic messaging, tailored to the SATS operational domain and coupled to the phase of flight in a logical, progressive sequence, facilitated their decision making while flying in IFR conditions. Responses to workload and SA subjective measures in conjunction with the usability questionnaires revealed that gating the messages to dedicated windows and providing on-condition cueing via softkeys delivered a sufficient level of information to assist in task execution without negatively impacting workload or SA. Future research endeavors will focus on minimum equipage for SATS operations through assessing the utility of the PA in self-separation tasks, non-normal conditions such as emergencies or transitions from IFR to visual flight, aural alerting, and alternative MFD design configurations.

ACKNOWLEDGMENTS

We thank Terry Abbott (Booze Allen Hamilton) for his assistance in defining the SATS HVO MFD requirements and Brian Baxley, the SATS HVO Team leader, for his guidance.

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